Mitglied der Helmholtz-Gemeinschaft

Vergleich des Standes und Aussichten von Brennstoffzellenfahrzeugen mit Batteriefahrzeugen

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Bad Honnef

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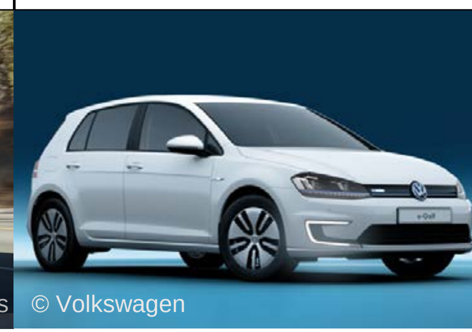
Vehicles

Select Battery Electric Vehicles

	Tesla 85D	e-Golf	BMW i3
Motor power	315 kW (428 PS)	85 kW (115 PS)	125 kW (170 PS)
Range (NEDC)	502 km	190 km	190 km
Consumption (NEDC)	16.9 kWh/100km	12.7 kWh/100km	12.9 kWh/100km
Battery capacity	85 kWh	24.2 kWh	18.8 kWh
Top speed	250 km/h	140 km/h	150 km/h
Acceleration 0-100 km/h	4.6 s	10.4 s	7.2 s
Base price	85,900 €	34,900 €	34,950 €



Sources:
- http://www.teslamotors.com/de_DE/models
- www.volkswagen.de/emobility
- http://www.bmw.com/com/de/newvehicles/i/i3/2013/showroom/technical_data.html

First Fuel Cell Vehicles in Market Introduction Phase

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1994 MB NECAR 1 (H_2)

1999 Honda FCX V1 (H_2)

2002 Honda FCX-V4: 1st FCV commercially certified *

2004 Clean Energy Partnership (D)

2012/ 13 Hyundai ix35 FCEV 1st manufact. plant

2015 Toyota Mirai 2nd series prod.

Fuel cell APUs for passenger cars, trucks, train, ships & airplanes

60s | 70s | 80s | 1990s | 2000s | 2010s

1966 GM Electrovan (H_2, AFC)

First FCV

2001 MB NECAR 5.2, methanol reformer

GM Chevrolet S-10 gasoline reformer

2001 Cold start at -20°C (GM)

2006 HT-PEM (Volkswagen)

2008-2009 Small series for demonstration projects

MB B-Class F-Cell | GM HydroGen4 | Honda FCX Clarity

Aromatic membrane -30…95 °C

* First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use

MB: Mercedes-Benz; GM: General Motors

All cars with PEFC except GM Electrovan with AFC

Audi, Chrysler, Daihatsu, Ford, GM, Honda, Hyundai, Kia, Mercedes-Benz, Nissan, Peugeot, Renault, SAIC, Suzuki, Toyota, VW

Commercial FC Vehicles

	Toyota Mirai	Hyundai iX35	Hyundai Tucson (2016)
Vehicle type	front-motor, front-wheel-drive, 4-passenger, 4-door sedan, one-speed direct drive	Electric reducer FWD, 5-seater [planetrary type mechanical varaible speed tranction drive]	Compact SUV, 5-seater, single-speed transmission FWD
Motor Power	115 kW Synchronous AC	100 kW	100 kW Induction motor
Torque	335 Nm (247 lb-ft)	300 Nm (30.6 kgm)	221 lb-ft or Nm
Fuel Cell Power	144 kW	-	100 kW
Range (NEDC)	502 km	594 km (144 liter H_2 tank)	424 km (265 mi)
Consumption (NEDC)	5.8/5.0 l/100km eq. (56/58 MPGe)	0.8896 kg H_2/100km city 0.9868 H_2/100km highway	-
Battery	NiMH	Lithium polymer 24 kW	Li-pol. 60 Ah, 24 kW, 0,95 kWh
Top speed	177 km/h	160 km/h	160 km/h
Acceleration	9 s 0-97 km/h (0-60 mph)	-	12,6 s 0-62 mph
Curb weight	1860 kg (4100 lb)	-	-
Base price	58,395 US$	-	Lease: 2,999 down; 499 monthly @36 months (incl. fuel & maintenance)

- http://www.caranddriver.com/toyota/mirai
- http://worldwide.hyundai.com/WW/Showroom/Eco/ix35-Fuel-Cell/PIP/index.html
- https://www.hyundaiusa.com/tucsonfuelcell/

Fuel Cell Systems

OEM	Model	Temperature [°C]	Pressure [bar]	Electrolyte	Bipolar Plate	P-density [kW/l]	Hydrogen tank pressure	H_2 consump. [kg/100km}
Daimler with Ford	F-CELL	~80	~2.0	perfluorated	graphitic		700	1.0
GM	Hydrogen4				graphitic		700	1.3
Honda	FCX Clarity	95	2.0	aromatic	metallic	1.9	350 (⇨700)	1.0
Hyundai	Ix35 FCV	70	0.2		metallic		700	0.95
Toyota with BMW	Mirai					3.1	700	1.0

Barbir, F., Chapter Ten - Fuel Cell Applications. in: BARBIR, F. (Ed.), PEM Fuel Cells (Second Edition), Academic Press, Boston, 2013, pp. 373-434. ISBN 978-0-12-387710-9

Mercedes-Benz Reports on 3.3M km of B-Class Fuel Cell Testing, Looks Ahead to Next Generation. http://www.greencarcongress.com/2013/11/20131125-daimler-fcv.html. Last access: February 25, 2015. Green Car Congress, BioAge Group, LLC.

Brachmann, T.: The Honda FCX Clarity - A viable Fuel Cell Electric Vehicle for today and beyond 2015? In proceedings: 18th World Hydrogen Energy Conference 2010, Essen, Germany, 16. bis 21. Mai 2010.

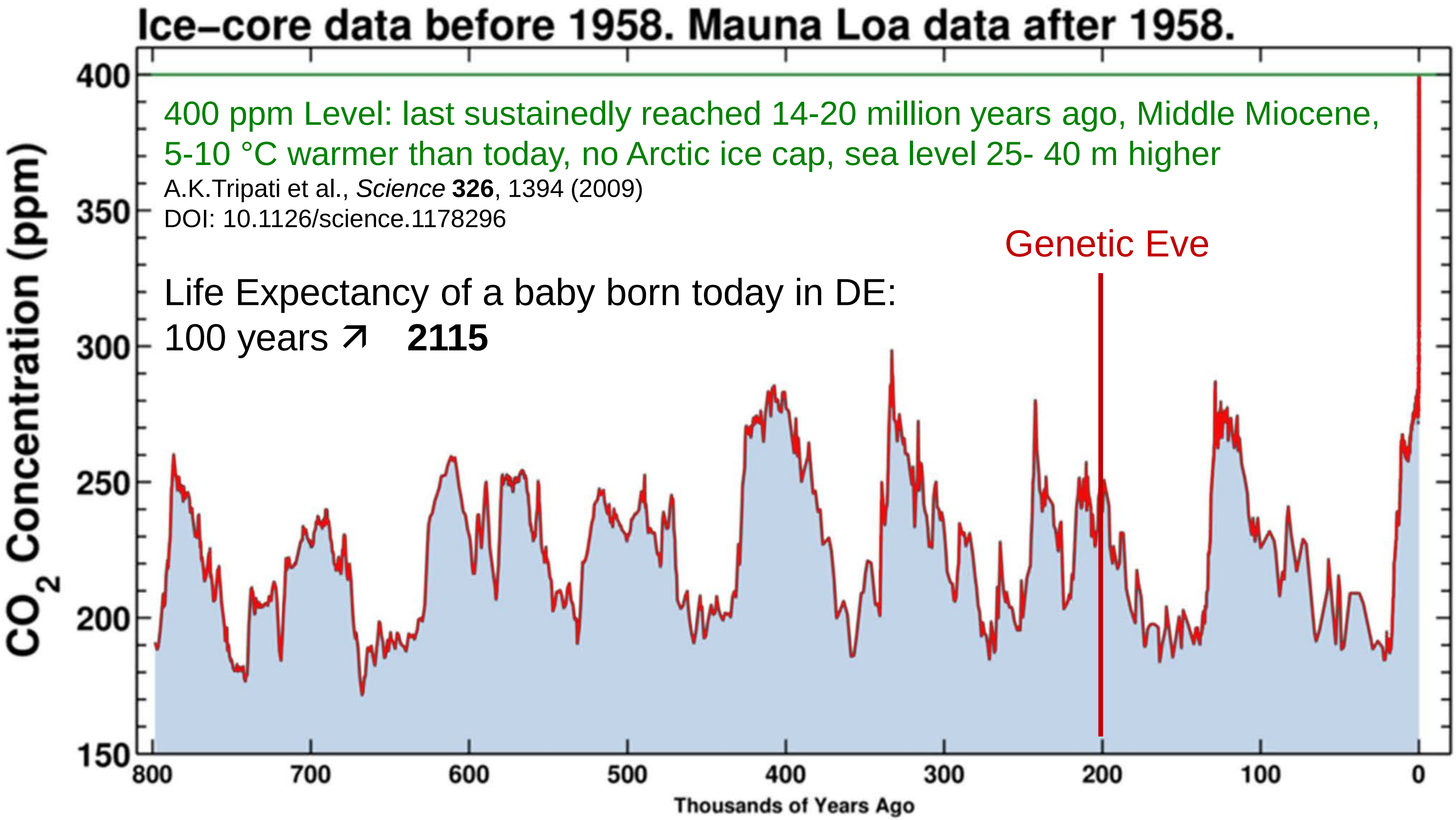
Toyota [2014]: Toyota Ushers in the Future With Launch of 'Mirai' Fuel Cell Sedan, Toyota Motor Europe, Brussels/Belgium, 2014.

ix35 Fuel Cell - Wasserstoffbetriebenes Brennstoffzellenfahrzeug, Hyundai Motor Deutschland GmbH, Offenbach, 2013

Eberle, U., et al., *Fuel cell electric vehicles and hydrogen infrastructure: status 2012*. In: *Energy & Environmental Science* 5 (2012), pp. 8780-8798.

Reasons, Scope and Timeline for Change

Modern CO_2 Level Rise is Unmatched in Human History



Future Energy Solutions need to be Game Changers

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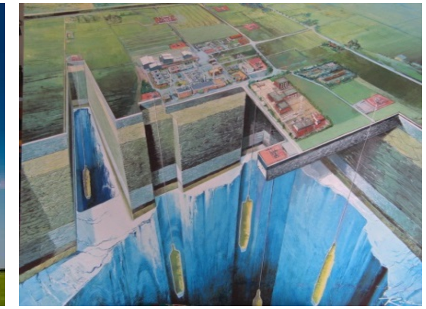


Drivers

- Climate change
- Energy security
- Competitiveness
- Local emissions

Grand Challenges

- Renewable energy
- Electro-mobility
- Efficient central power plants
- Fossil cogeneration
- Storage
- Transmission
- Interconnect the energy sectors to leverage synergies

Goals

- 2 degrees climate goal requires ……………. 50% ….by 2050 worldwide
- G8 goal ……………………………………….80% ….by 2050 w/r 1990
- Germany to reduce GHG emissions by …….80-95% by 2050 (w/o nuclear)

GHG Emissions Shares by Sector in Germany (2010)

	Emissions		Remedies (major vectors)
Energy sector	37%		
• Power generation	30%	→	22.5 % Renewables
Transport (90% petroleum-based)	17%		
• Passenger vehicles	11%	→	8.3 % **Hydrogen** / **battery vehicles**
• Trucks, buses, trains, ships, airplanes	6%	→	4.5 % Liquid fuel substitutes (biomass/CO_2-based; **hydrogenation**)
Residential	11%		
• Residential heating (electricity in power generation)	11%	→	8.3 % Insulation, heat pumps etc.
Industry, trade and commerce	23%		
• Industry	19%	→	9.5 % CO_2-capture from steel, cement, ammonia; **hydrogen** for CO_2-use
• Trade and commerce	4%		25 % already cleaned-up since 1990
Agriculture and forestry	8%		78.1% clean-up
Others	4%		
Total	100%		

Source: Emission Trends for Germany since 1990, Trend Tables: Greenhouse Gas (GHG) Emissions in Equivalents, without CO_2 from Land Use, Land Use Change and Forestry Umweltbundesamt 2011

Transport-related values: supplemented with *Shell LKW Studie – Fakten, Trends und Perspektiven im Straßengüterverkehr bis 2030*.

Timeline for CO_2-Reduction and the Implication of TRL Levels

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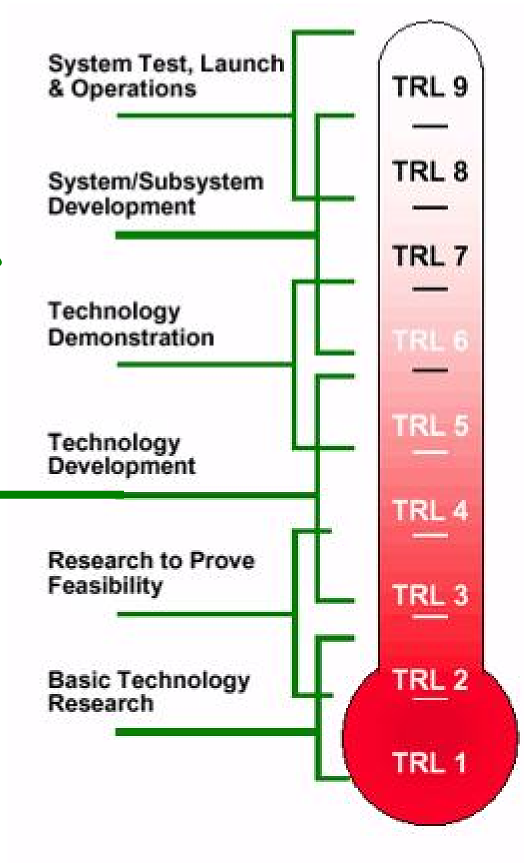
- **2050:** 80% reduction goal fully achieved
- **2040:** start of market penetration
- **2030:** research finalized for 1st generation technology

Development period: unil 2040

Research period: until 2030

⇒ 15 years left for research => TRL 5 and higher

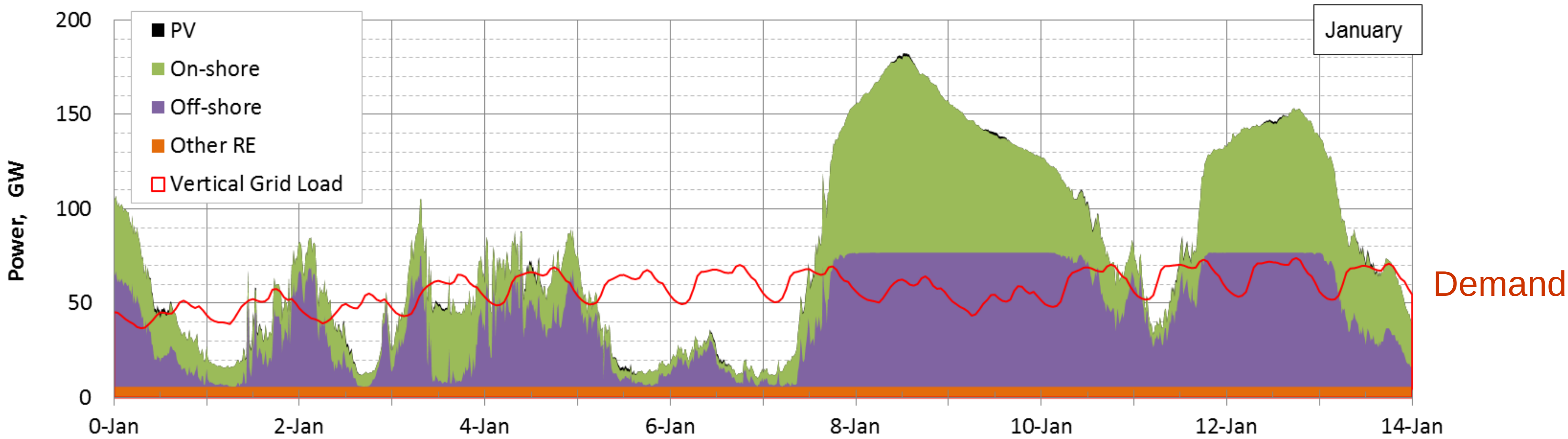
TRL 4 at least

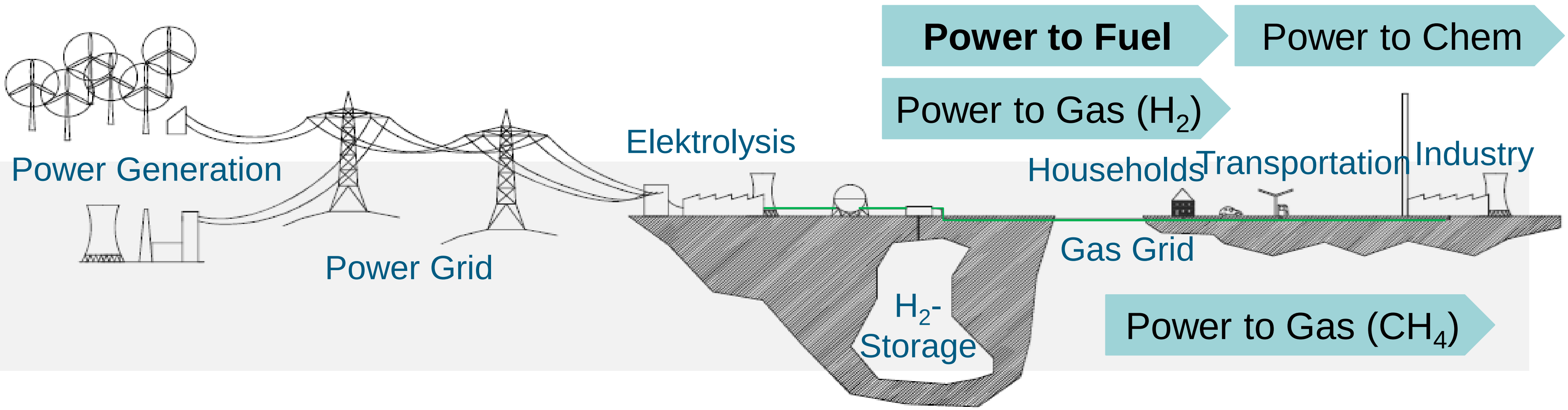


This is not to say research at lower TRL levels is not useful, it will just not contribute to the 2050 goal

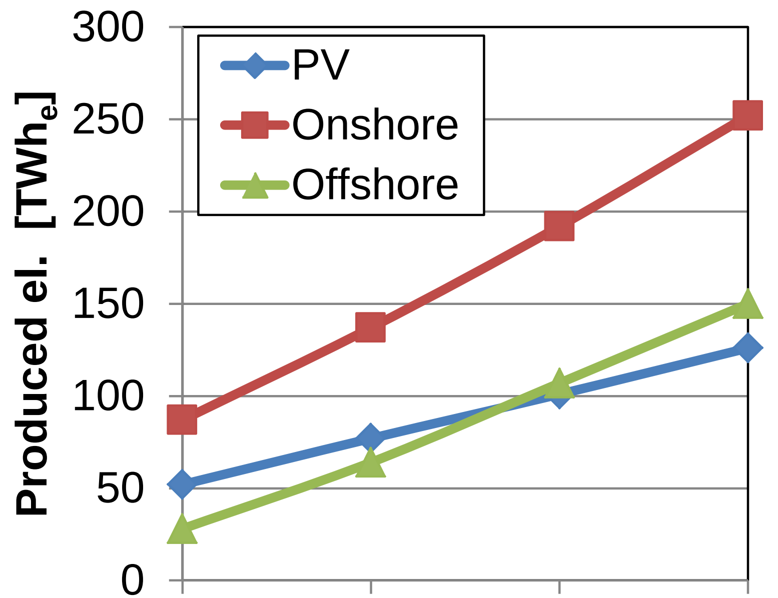
Renewable Power Generation

Excess Power is Inherent to Renewable Power Generation





Development of Renewables According to Current German Policy



		2020	2030	2040	2050
Peak excess power*	GW_e	22	55	90	125
Excess energy*	TWh_e	2,5	30	100	200
Minimum storage size**	TWh	0,9	6	12	17

Overcapacity in Power is Inherent for Full Renewable Energy Supply

renewable power needed = capacity factor x average power demand

- Averaged power demand for Germany: ~60GW
- Capacity factor for full renewable power supply
  - Onshore wind → 4.4
  - Offshore wind → 2.2

  } @ no losses for reconversion considered

→ Installed renewable power exceeds power demand on a regular basis

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Why are There so Many Contradictory Assessments on Storage?

The necessity of using chemical energy storage depends on:

- The time-line

  The shorter the time-line the less storage will be needed. The need of storage at an earlier time might not be in line with the lead-time needed for furnishing later storage requirements.

- The energy sectors included

  If **only the power sector** gets considered, **storage will be necessary much later** compared to scenarios which look into a comprehensive CO2 clean-up of whole energy sector, including transportation and industry. Households might not have that a strong impact on the storage scenarios.

  Scenarios considering just the power sector at 2030 consistently report that no storage will be needed. **That does not take into account** that **additional electrical energy** will be **needed for transportation and industry**, currently fueled by fossils.

- The level of penetration of renewable energy

  If only **intermediate levels of RE** penetration is envisaged / imagined there is **little need for storage.** Yet, that is not in line with political goals and societal requirements.

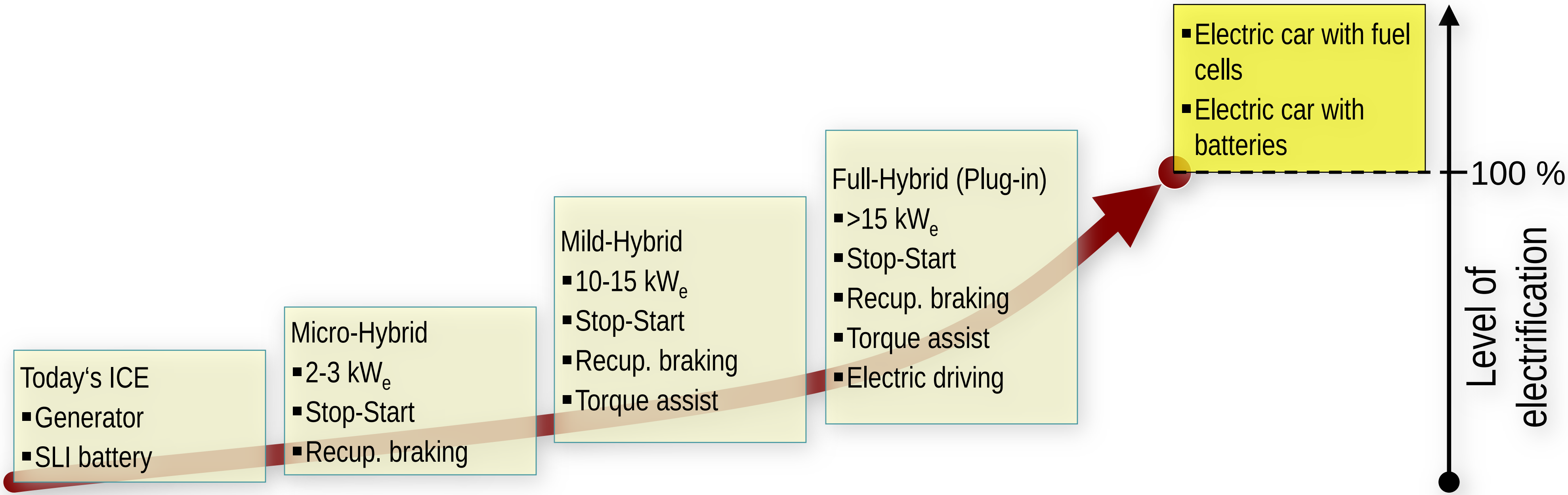
- Whether the political goals (of the German Energy Strategy) are accepted / taken seriously

The assessments depend on the assumptions to an unusual extent

Vehicles in Use

Electrification of Cars Increases

- Re-orientation in the energy sector is related to energy-strategic targets: energy imports, environmental impact, economic competitiveness
- Transportation: i.a. new powertrains and fuels for road transport
  - *Advanced and increasingly hybridized powertrains with internal combustion engines*
  - *Plug-in hybrids with internal combustion engines*
  - *Zero emission electric powertrains with battery*
  - *Zero emission electric powertrains with fuel cells*



ICE: internal combustion engine
SLI: starting, lighting and ignition

What are New Components of BEV and FCV?

Powertrain

- Electric motor/generator and gearbox
- High-voltage power distribution
- Electric braking
- Power electronics and operational strategy

Comfort and Safety

- Electric steering
- Air conditioning (electrically powered, highly-efficient)

FCV only

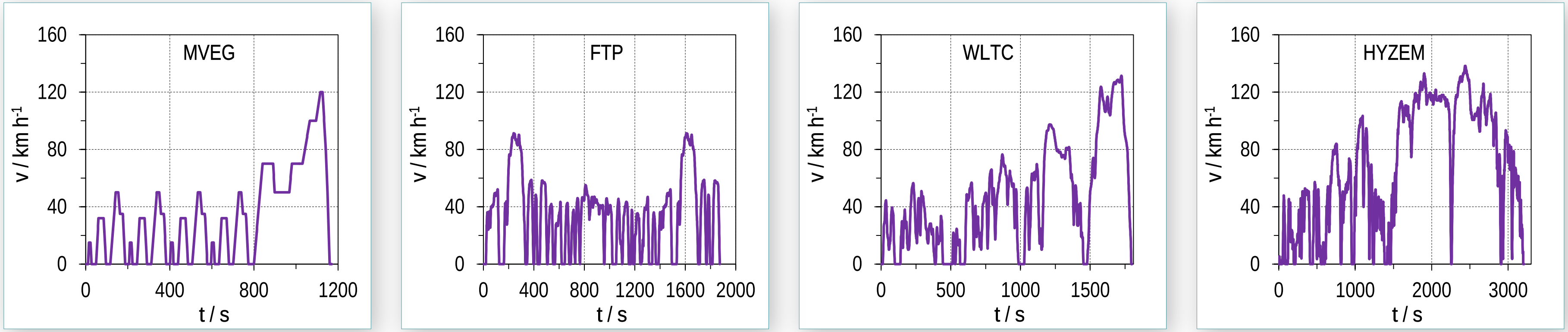
- Fuel cells system and gas storage
- Hybrid battery including battery management system

BEV only

- Traction battery including battery management system

Simulation-Based Fuel Economy Assessments

- Quantification of fuel use in drive cycles using:
  - *Quasi-stationary or dynamic simulation models with physical or map-based component description*
  - *Examples: AVL CRUISE (AU), ADVISOR (USA), PSAT Engine/Autonomie (USA)*
  - *At IEK-3: own simulation model development based on Matlab/Simulink®*
- Load profiles:
  - *mechanical: drive cycles for covering different user profiles, e.g.*

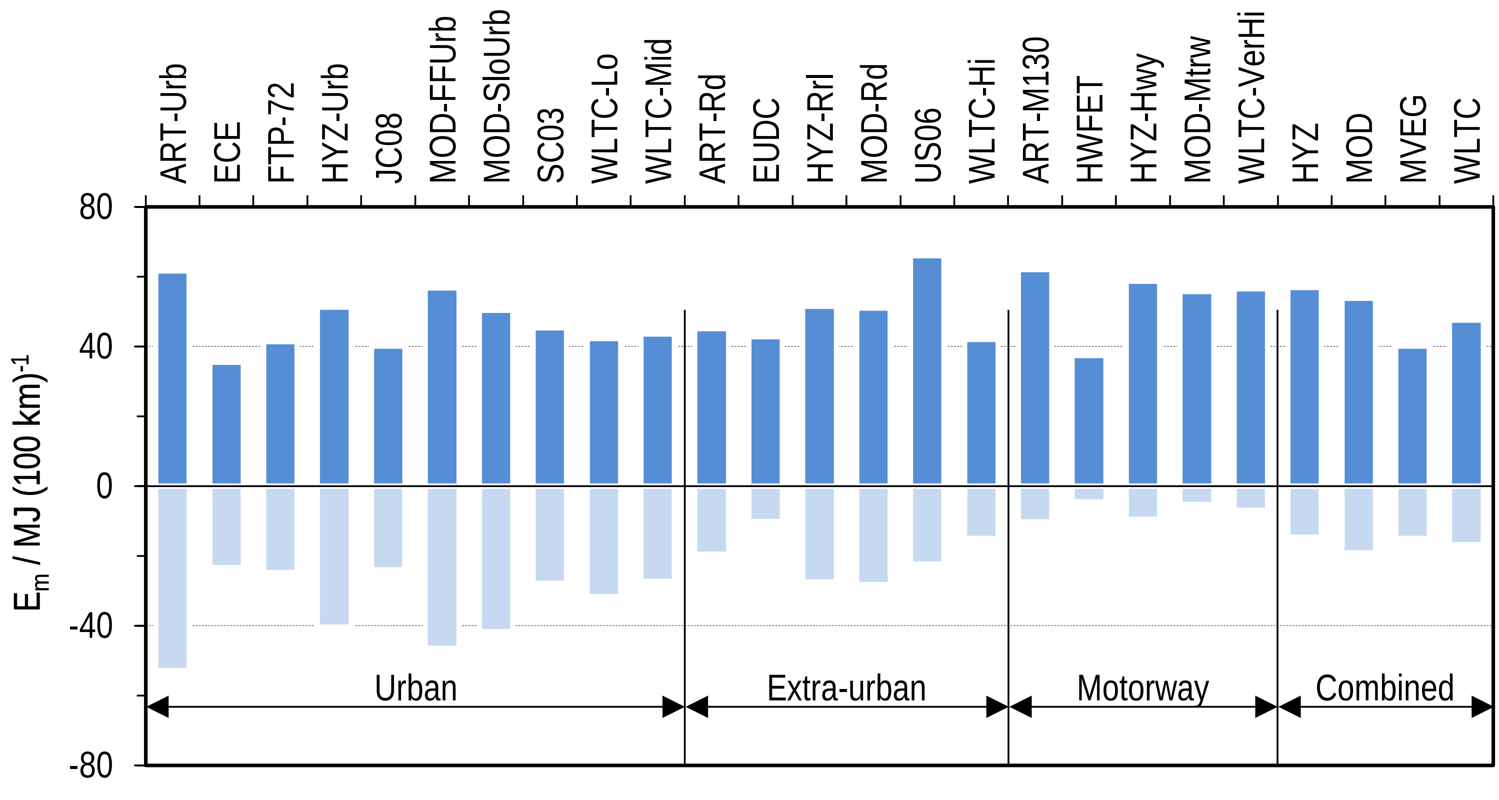


European standard cycle for type approval | US standard cycle for type approval | Worldwide harmonized Light duty Test Cycle | Empirically assessed driving profile

  - *Electric: base load and additional consumers of the 14 V onboard grid*
  - *Thermal: cabin conditioning (heating and cooling)*

Drive Cycle has Great Impact on Mechanical Energy Requirement of Cars

- The figure shows positive (acceleration) and negative (braking) energy requirements of a compact car according to [1]
- Vehicle weight: 1251 kg; frontal area: 2.1 m²; air drag coefficient: 0.32



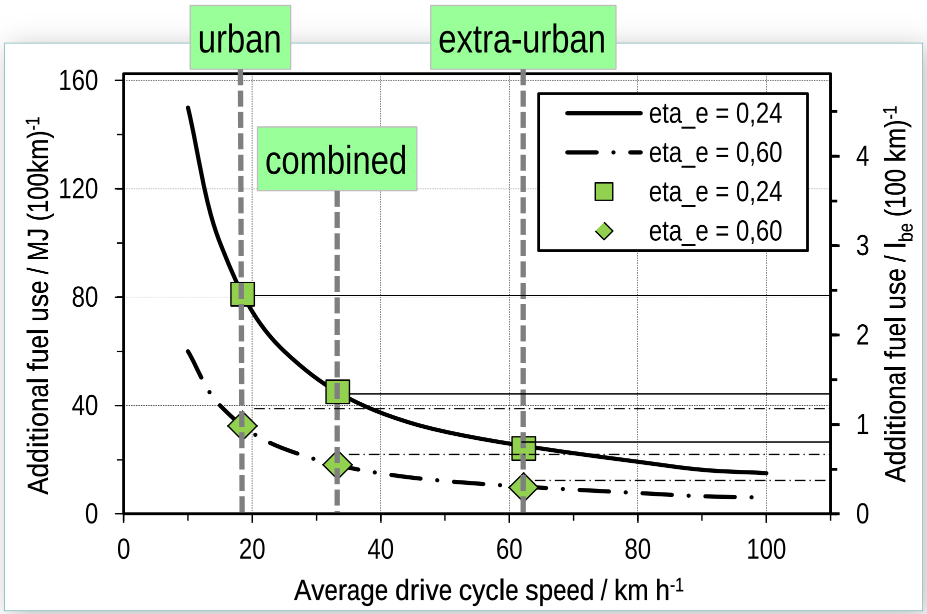
Grube (2014): Grube, T.: Potential der Stromnutzung in Pkw-Antrieben zur Reduzierung des Kraftstoffbedarfs. Technische Universität Berlin, Fakultät V - Verkehrs- und Maschinensysteme, Dissertation. 2014

Auxiliary Power Particularly Relevant at Low Average Speed

Fuel consumption of vehicles is defined by

- time dependent velocity, e.g. of drive cycle for passenger car type approval
- auxiliary power requirement of electric onboard grid, heating and cooling

Additional fuel use at 1kW$_e$ auxiliary power



Values related to MVEG drive cycle (EU regulation 80/1268/EWG [1])

Values for the European Drive Cycle (MVEG)

Passenger car with:

ICE	Fuel cells
$\eta_{diff,m} = 0{,}4;\ \eta_G = 0{,}6$	
$\eta_e = \eta_{diff,m} * \eta_G = 0{,}24$	$\eta_e = 0{,}6$
□ 0,7 – 2,5 l_{ge} $(100km)^{-1}$	△ 0,3 – 1,0 l_{ge} $(100km)^{-1}$

Indices: diff: differential; e: electric; G: generator m: mechanical; SBS: electricity provision; l_{ge}: liters of gasoline equivalent; KS: fuel

Sources: [1] Richtlinie des Rates vom 16. Dezember 1980 über die Kohlendioxidemissionen und den Kraftstoffverbrauch von Kraftfahrzeugen (80/1268/EWG) - konsolidierte Fassung vom 19.02.2004. 2004

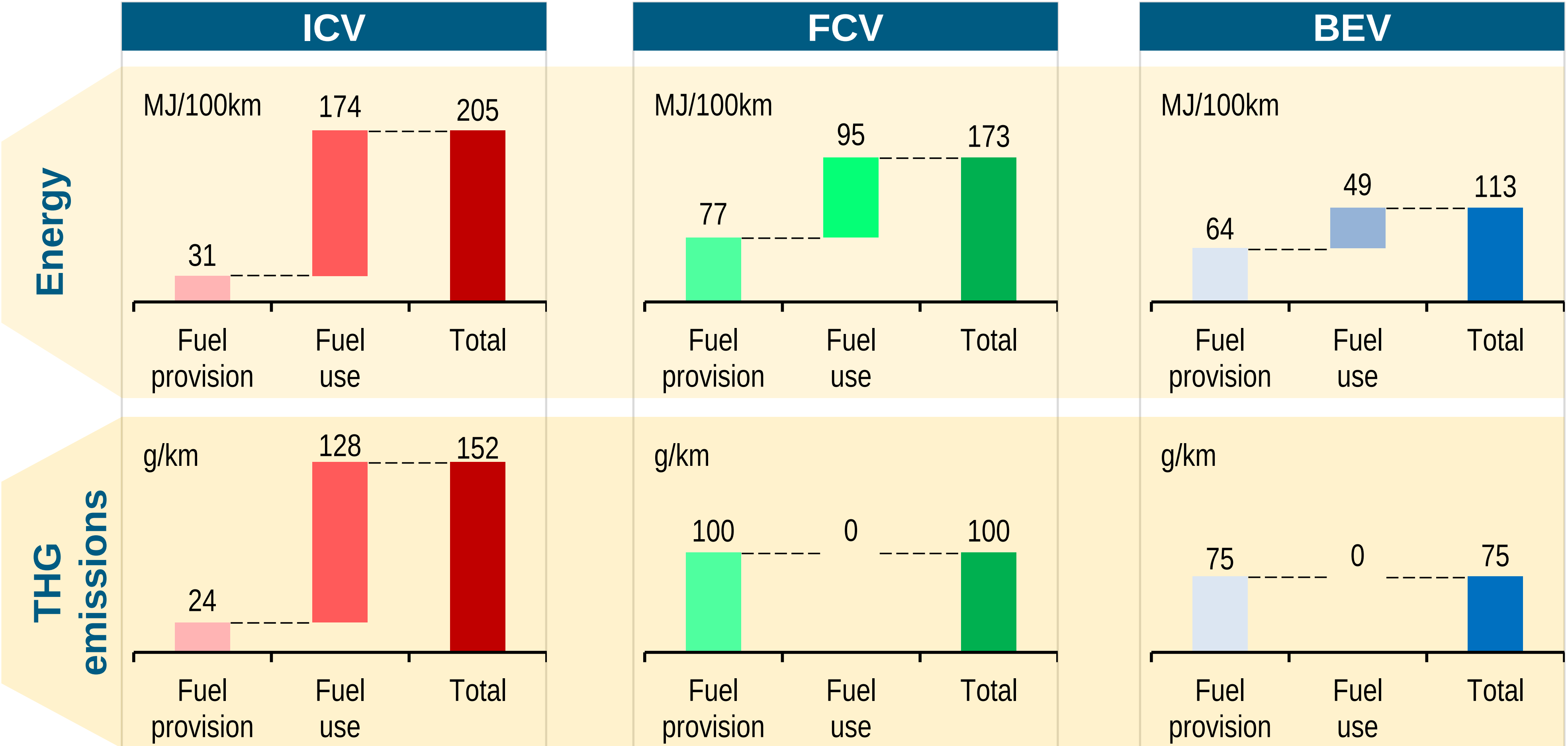
Assumptions for Well-to-Wheel Data

	Primary energy	Fuel production and distribution	Fuel use
BEV standard case	German Electricity mix: 36 % efficiency, 559 g_{CO2}/kWh_e	-	13 $kWh_e/100km$
BEV Renewable Energy Case	Renewable Electricity, per definition 100 % primary energy; natural gas power plants for pos. residual energy, 62 g_{CO2}/kWh_e	-	13 $kWh_e/100km$
FCV standard case	Natural gas provision: 85 % efficiency	Steam reforming of natural gas; pipeline distribution; 880 bar at dispenser	0.8 $kg_{H2}/100km$
FCV renewable energy case	Renewable Electricity not usable in the grid, per definition 100 % primary energy	Electrolysis with 70 % efficiency; pipeline distribution; 880 bar at dispenser	0.8 $kg_{H2}/100km$

Well-to tank data: IEK-3 Energy Concept **and** JEC - Joint Research Centre-EUCAR-CONCAWE collaboration: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - Well-to-Tank Report, Version 4a, 2014. European Commission, Joint Research Centre, 2008; **Tank-to-wheel data**: Grube (2014): Grube, T.: Potential der Stromnutzung in Pkw-Antrieben zur Reduzierung des Kraftstoffbedarfs. Technische Universität Berlin, Fakultät V - Verkehrs- und Maschinensysteme, Dissertation. 2014

GHG: Greenhouse gas emissions; ICV: Internal combustion engine vehicle; BEV: Battery vehicle; FCV: Fuel cell vehicle

Well-to-Wheel: Energy and GHG comparison (Reference Case)



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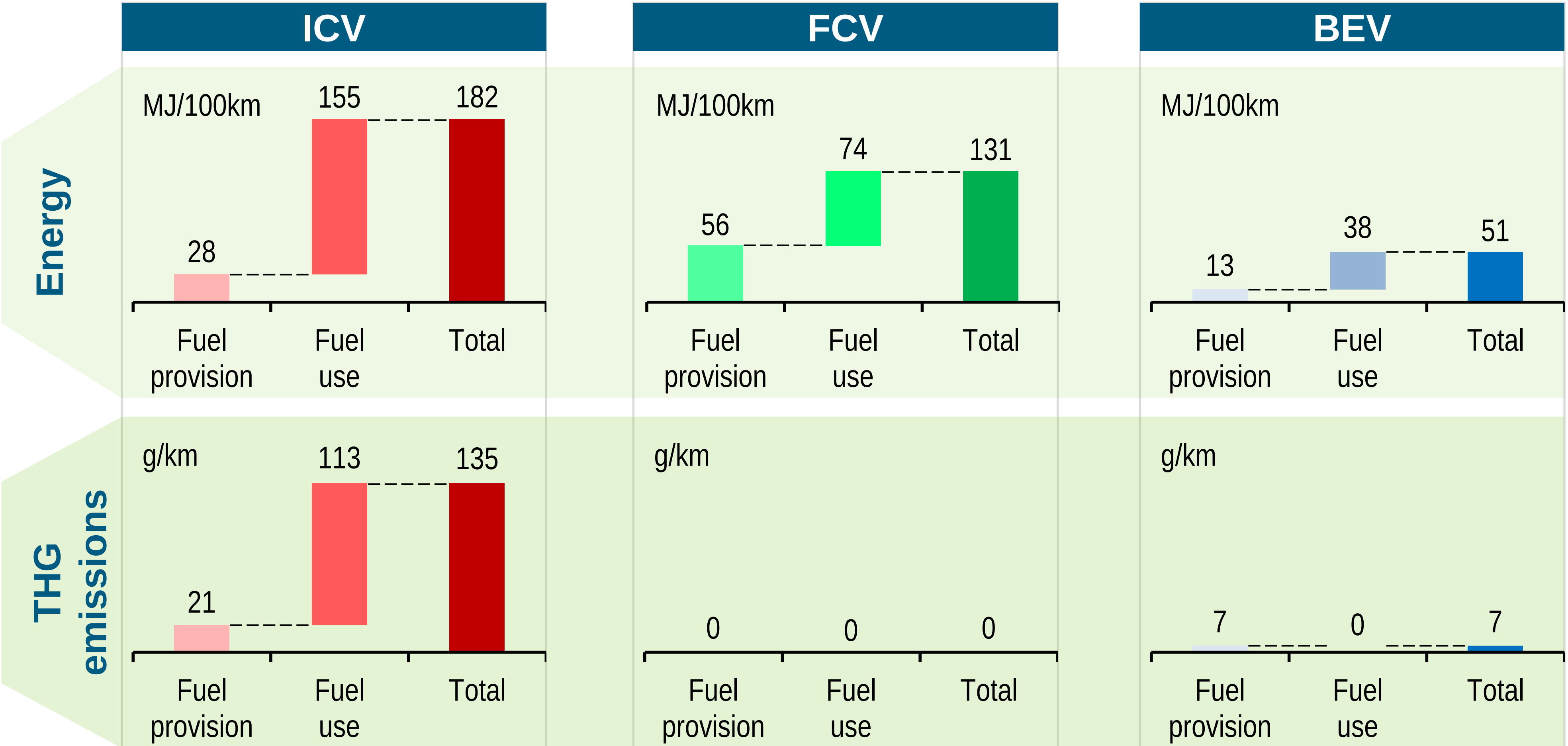
Well-to-Wheel: Energy and GHG comparison (Renewable Energy Case)



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GHG: Greenhouse gas emissions; ICV: Internal combustion engine vehicle; BEV: Battery vehicle; FCV: Fuel cell vehicle

Well-to-Wheel: Primary Energy Use and GHG Emissions
(Reference Case)

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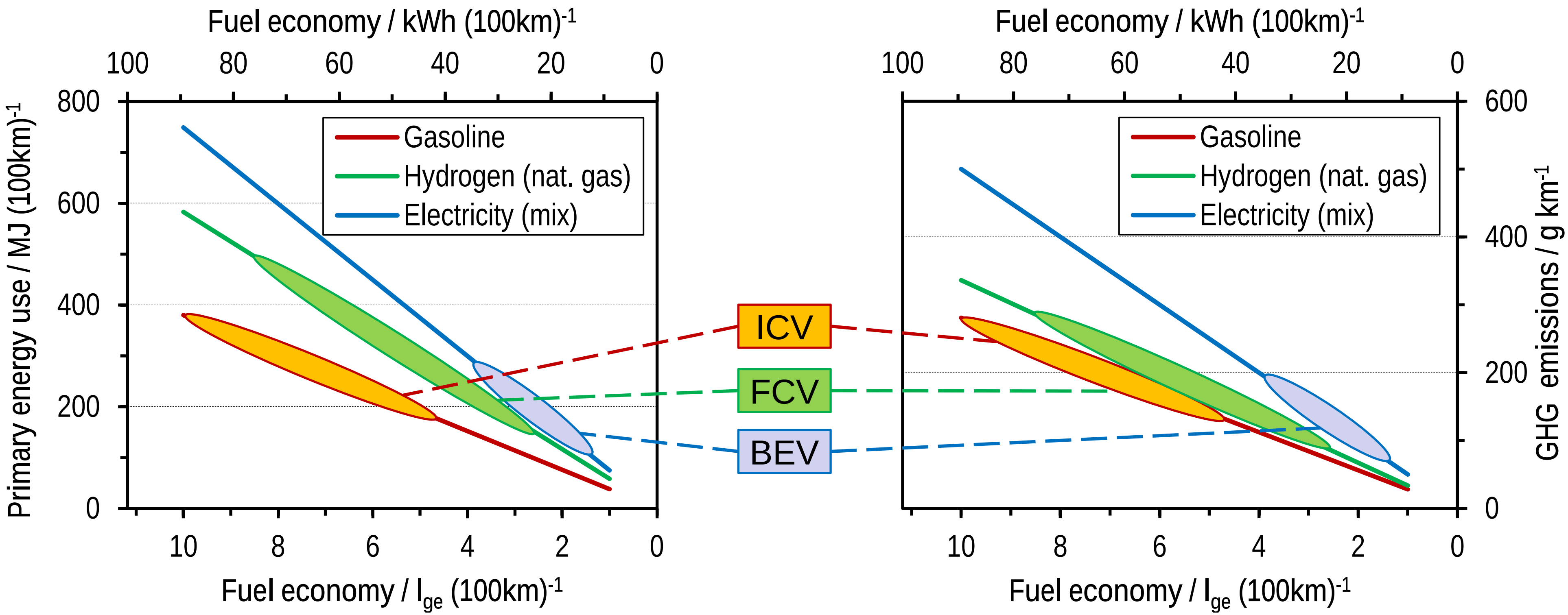
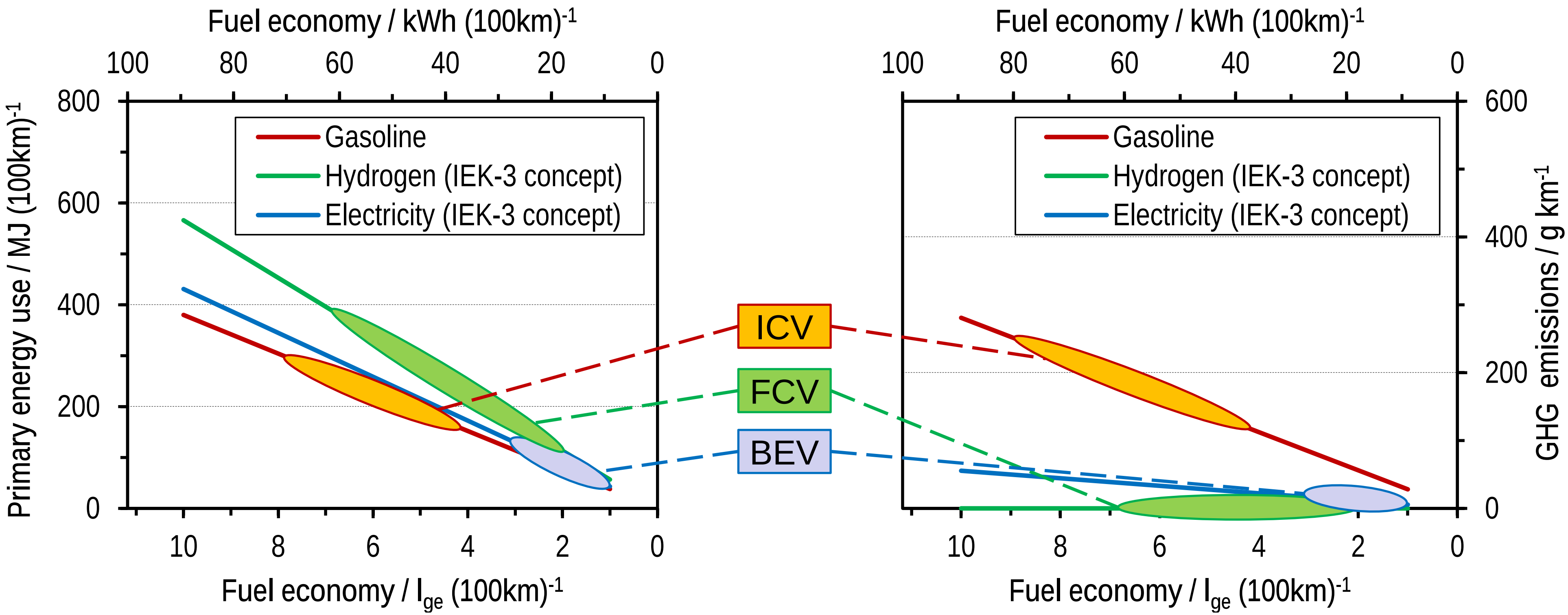


Well-to tank data: JEC - Joint Research Centre-EUCAR-CONCAWE collaboration: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - Well-to-Tank Report, Version 4a, 2014. European Commission, Joint Research Centre, 2008.

Tank-to-wheel data: Grube, T.: Potential der Stromnutzung in Pkw-Antrieben zur Reduzierung des Kraftstoffbedarfs. Technische Universität Berlin, Fakultät V - Verkehrs- und Maschinensysteme, Dissertation. 2014;
-> scenario „Standard“, values for all cycles and for all onboard grid load cases.

ge: gasoline equivalent; **GHG:** greenhouse gas; **mix:** electricity mix for Germany (2013); **nat. gas:** natural gas;

Well-to-Wheel: Primary Energy Use and GHG Emissions
(Renewable Energy Case)



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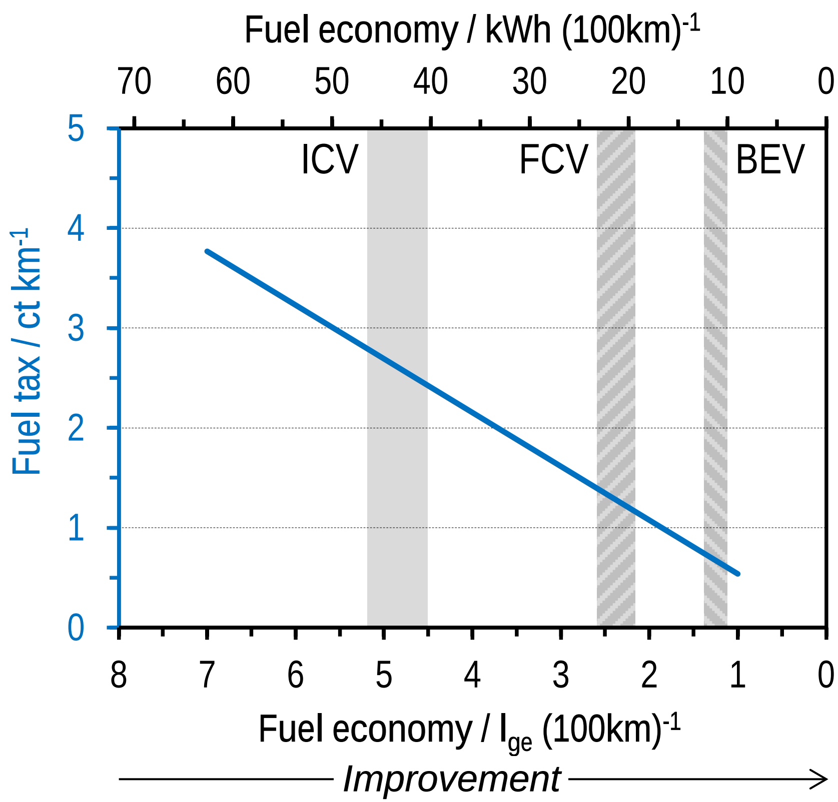
Tank-to-wheel data: Grube, T.: Potential der Stromnutzung in Pkw-Antrieben zur Reduzierung des Kraftstoffbedarfs. Technische Universität Berlin, Fakultät V - Verkehrs- und Maschinensysteme, Dissertation. 2014;
-> scenario „Zukunft", values for all cycles and for all onboard grid load cases.

ge: gasoline equivalent; **GHG:** greenhouse gas; **mix:** electricity mix for Germany (2013); **nat. gas:** natural gas;

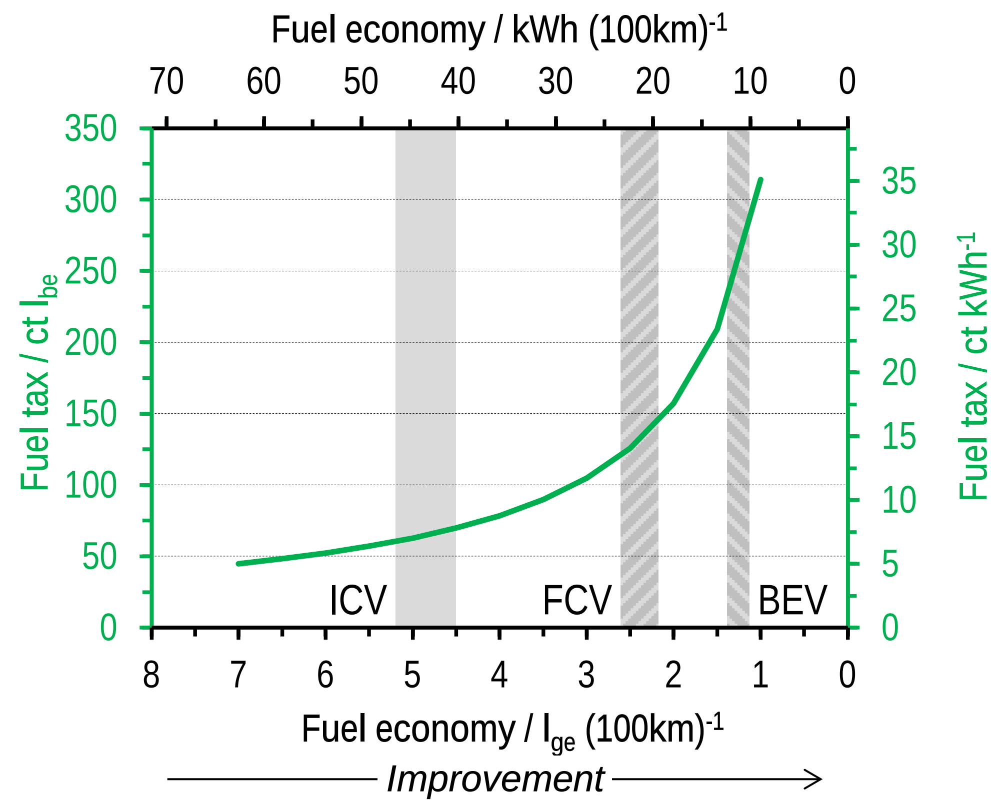
Fuel Tax Discussion

Fuel tax in Germany [ct/l]: 65.45 (gasoline), 47.04 (diesel)

Case 1: tax is constant on an energy basis[1)]
Average for energy equivalent: **53.8 ct/l$_{ge}$**



Case 2: tax revenue is constant[2)]
Average for distance equivalent[3)]: **3.14 ct/km**



1) Fuel tax average of gasoline and diesel
2) Assuming constant passenger kilometers and vehicle occupation
3) 6.0 l/100 km, gasoline car; 5.0 l/100km diesel car

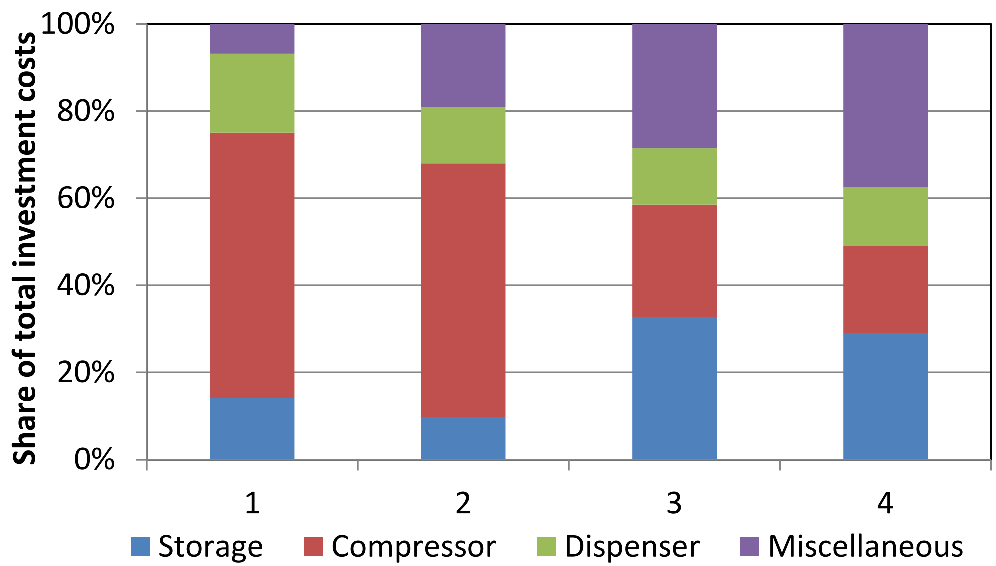
ge: gasoline equivalent
Tank-to-wheel data of ICV, BEV and FCV according to Grube (2014), values for MVEG cycle for the scenario “Zukunft”and for base load only

Hydrogen Refueling Stations

- Investment costs for large scale H_2 refueling stations (capacity of 1500 kg_{H2}/day) are predicted to drop to < 2 million Euro per station[1)]
- Linde set up production line for 50 H_2 refueling stations per year in Vienna, Austria
  → Reduction of investment costs from 1.5 to 1 million Euro per refilling station (smaller scale)[5)]

- Total costs and cost distribution vary drastically in literature according to station size, type of compressor, location and assumptions

- Main cost drivers are compressors and high-pressure storage
  → 50-75 % of total investment costs



1) M. Wietschel, U. Bünger: Vergleich von Strom und Wasserstoff als CO_2-freie Endenergieträger, 2010
2) H2-Roadmap: AP1 “Prinzipielle Anforderungen an die Infrastruktur”, DWV, 2003
3) B. Gim, W.L. Yoon: Analysis of the economy of scale and estimation of future hydrogen production costs at on-site hydrogen refueling stations in Korea, IJHE, 2012
4) J.X. Weinert et al.: Hydrogen refueling station costs in Shanghai, IJHE, 2007
5) http://www.hzwei.info/blog/2014/10/08/linde-startet-serienproduktion-von-h2-tankstellen/

Refueling and Charge Time for 100 km Operational Range

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Assumptions:

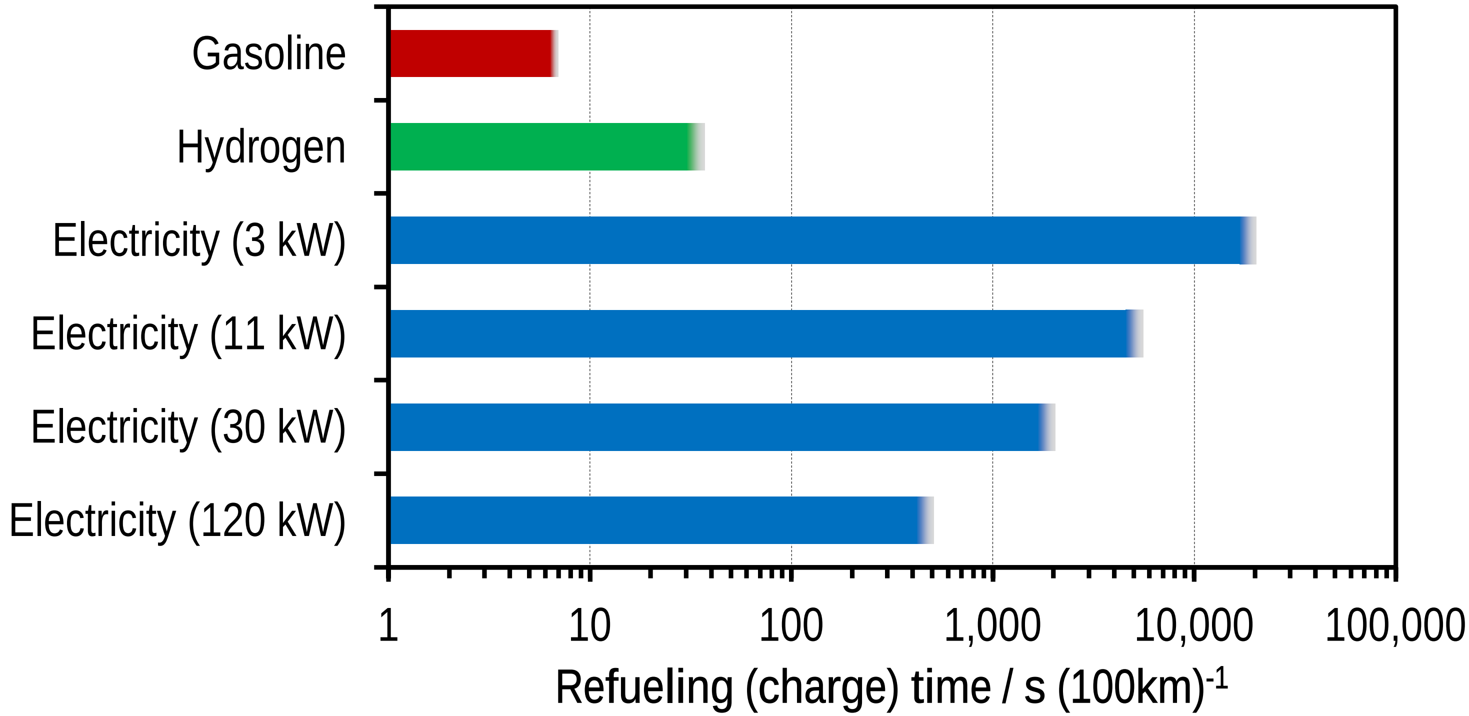
- Gasoline (l/min): **50**
- Hydrogen (kg/100km): **1**
- Electric Power (kW): **3 | 10 | 30 | 120***

Fuel use [1]:

5.3 (4.8) l/100 km (Gasoline-ICE)

0.84 (0.65) kg/100km (FCV)

14 (11) kWh/100km (BEV)



3 kW: wall outlet | 10 kW: high-power wall outlet | 30 kW: public charging station | 120 kW: Tesla Supercharger

Grube (2014): Grube, T.: Potential der Stromnutzung in Pkw-Antrieben zur Reduzierung des Kraftstoffbedarfs. Technische Universität Berlin, Fakultät V - Verkehrs- und Maschinensysteme, Dissertation. 2014

Alternative Drive Trains for Trucks

Data of a conventional 40 t trailer truck*:

- Engine Power: 350 kW
- Mean efficiency of diesel engine (Euro VI): 43.5 %
- Diesel consumption (Long Haul Cycle): 34.5 l_{Diesel}/100km (12.4 MJ/km)
- Tank volume: 800 l
- Range: 2300 km

Replacement of conventional diesel engine by battery or fuel cell driven electric motor:

Fuel cell driven electric power train:

- Mean efficiency of fuel cell: 60 %
- Hydrogen consumption (Long Haul Cycle):
  → 7.5 kg_{H2}/100km (9.0 MJ/km)
- Required hydrogen tank (for same range):
  → 172 kg_{H2}
- Required hydrogen tank volume (0.83 kWh/l) and mass (1.7 kWh/kg): 6.9 m³ and 3.4 t

Battery driven electric power train:

- Mean efficiency of battery: 90 %
- Electricity consumption (Long Haul Cycle):
  → 166 kWh_{el}/100km (6.0 MJ/km)
- Required battery capacity (for same range):
  → 3829 kWh
- Required battery volume (300 Wh/l) and mass (150 Wh/kg): 12.7 m³ and 25.5 t

→ Low energy density of batteries and compressed hydrogen make use in heavy transport unlikely

*Umweltbundesamt: Zukünftige Maßnahmen zur Kraftstoffeinsparung und Treibhausgasminderung bei schweren Nutzfahrzeugen, 2015

Cruising Range Depends on Drive Cycle and Auxiliary Power

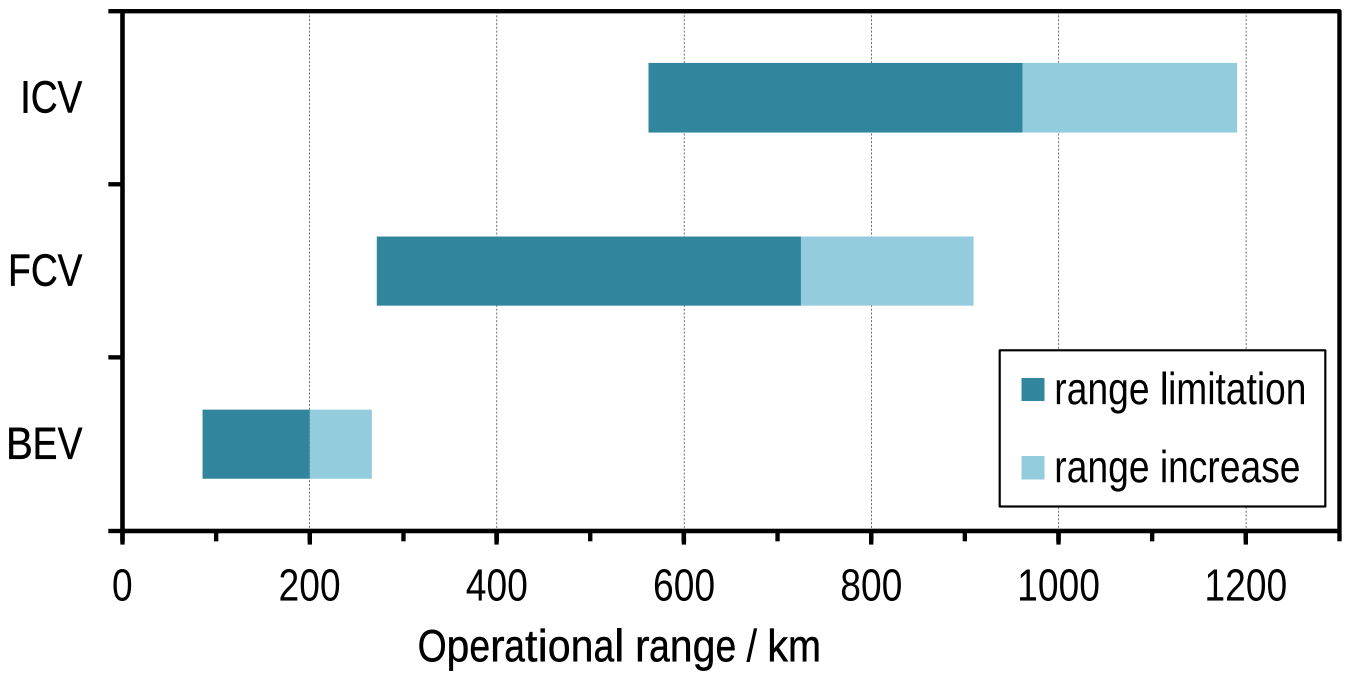
Operational range increase or limitation for

- Internal combustion engine vehicles (ICV)
- Fuel Cell Vehicles
- Battery vehicles

Definitions according to [1]

- Compact car
- Scenario „Zukunft“

- All 25 drive cycles
- All onboard load cases
- Maximum and minimum fuel consumptions have been selected
- Nominal range according to fuel storage:
  50 l for ICV
  5 kg H2 for FCV
  24 kWh for BEV

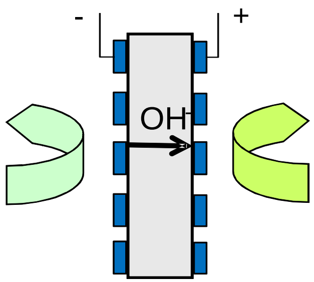


In extreme cases (low cycle speed and high auxiliary power) operational range can be reduced by up to 60 %

Hydrogen Generation, Storage and Transmission

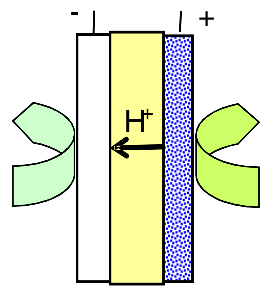
Options for Water Electrolysis

Alkaline electrolysis



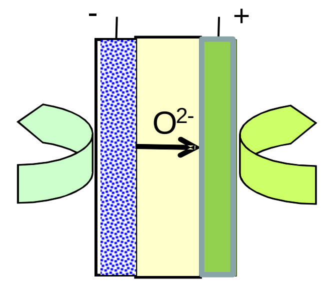
- Mature technology
- <3.6 MW stacks
- Plants <156 MW
- Ni catalysts
- 750 €/kW - 1000€/kW

PEM - electrolysis



- Development stage
- < 1 MW in development
- Pt and Ir as catalysts
- Simple plant design
- €1500@ 2015
- € 500@ 2030 (FZJ)

Solid Oxide Electrolysis



- Laboratory stage
- Very high efficiency
- Brittle ceramics
- Hence, slow scale-up
- Just cost estimations

Decouple Power and Energy for Long-term Storage

Assumption: storage may add about the same price tag to the energy delivered, be it

- Short-term storage, or
- Long-term storage

	Storage cycles / a [1/a]	Relative allowable invest / kWh* [%]	Energy required [GWh]	Energy specific investment cost [€ / kWh]	Power required [GW]	Additional cost for conversion units (electrolyzer) [€/kW]
Short-term	100 - 1000	100%	some GWh	Batteries 100-200	some 10GW	none
Long-term	1 - 10	1%	some 1000 GWh	Salt cavern < 1	some 10GW	500 €/kW

Uncoupling Power and Energy

Batteries : Power and energy scale linearly with unit size

Hydrogen: **Power** scales less than **energy,** this makes storage affordable

↓ **Electrolyzers**

↓ **Gas caverns:** allow for quick discharge ⇨ serve dynamic requirements

Geologic Gas Storage Facilities

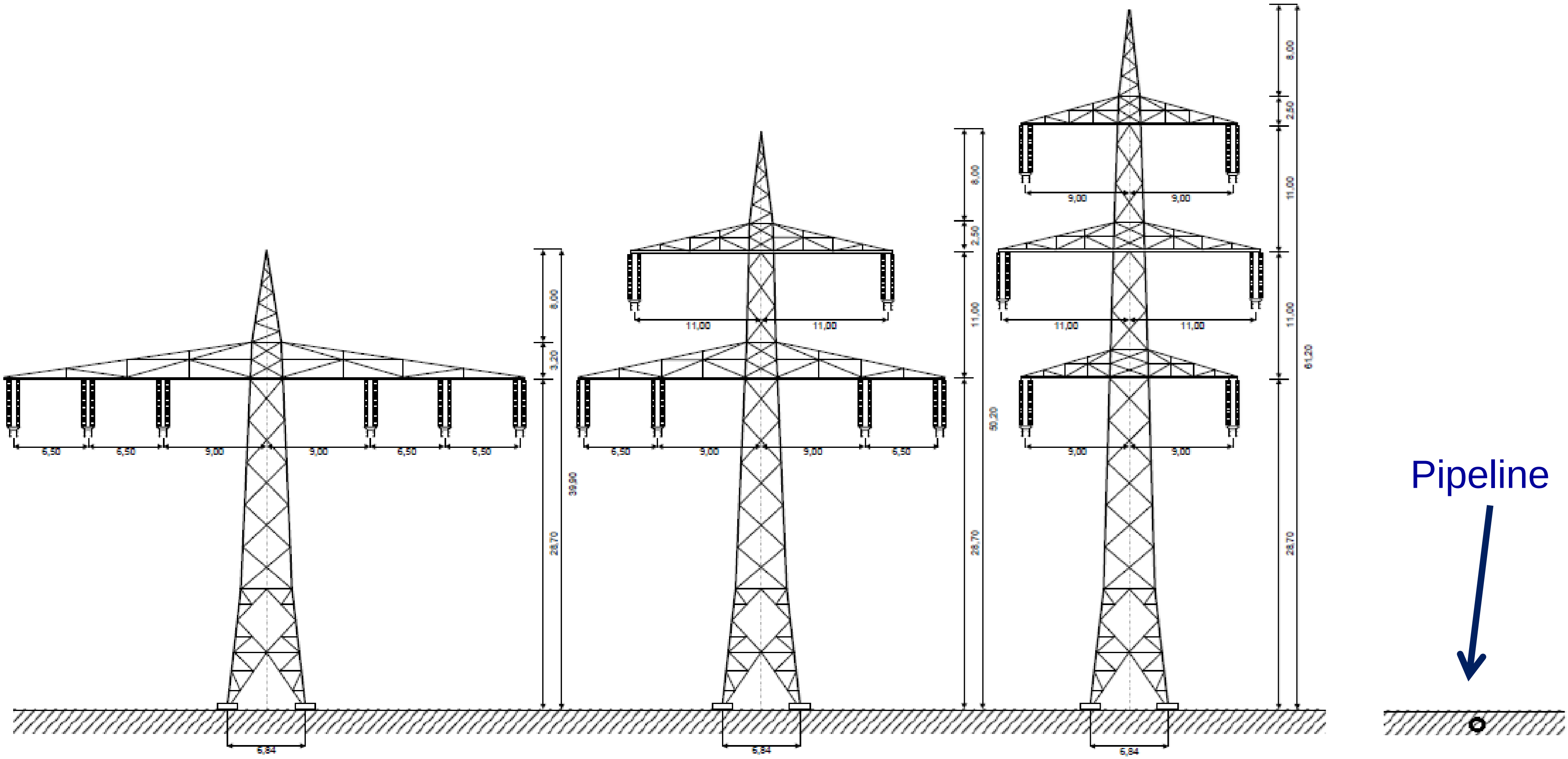
	Depleted oil / gas fields	Aquifers	Salt caverns	Rock caverns / abandoned mines
Working volume [scm]	10^{10}	10^{8}	10^{7}	10^{6}
Cushion gas	50 %	up to 80 %	20 - 30 %	20 - 30 %
Gas quality	reaction and **contamination** with present gases, microorganism and minerals		saturation with water vapor	
Annual cycling cap.	only seasonal		seasonal & frequent	

Spatial Requirements for Transmission

JÜLICH
FORSCHUNGSZENTRUM

Width of protective strips

70 m | 57 m | 48 m | 10 m



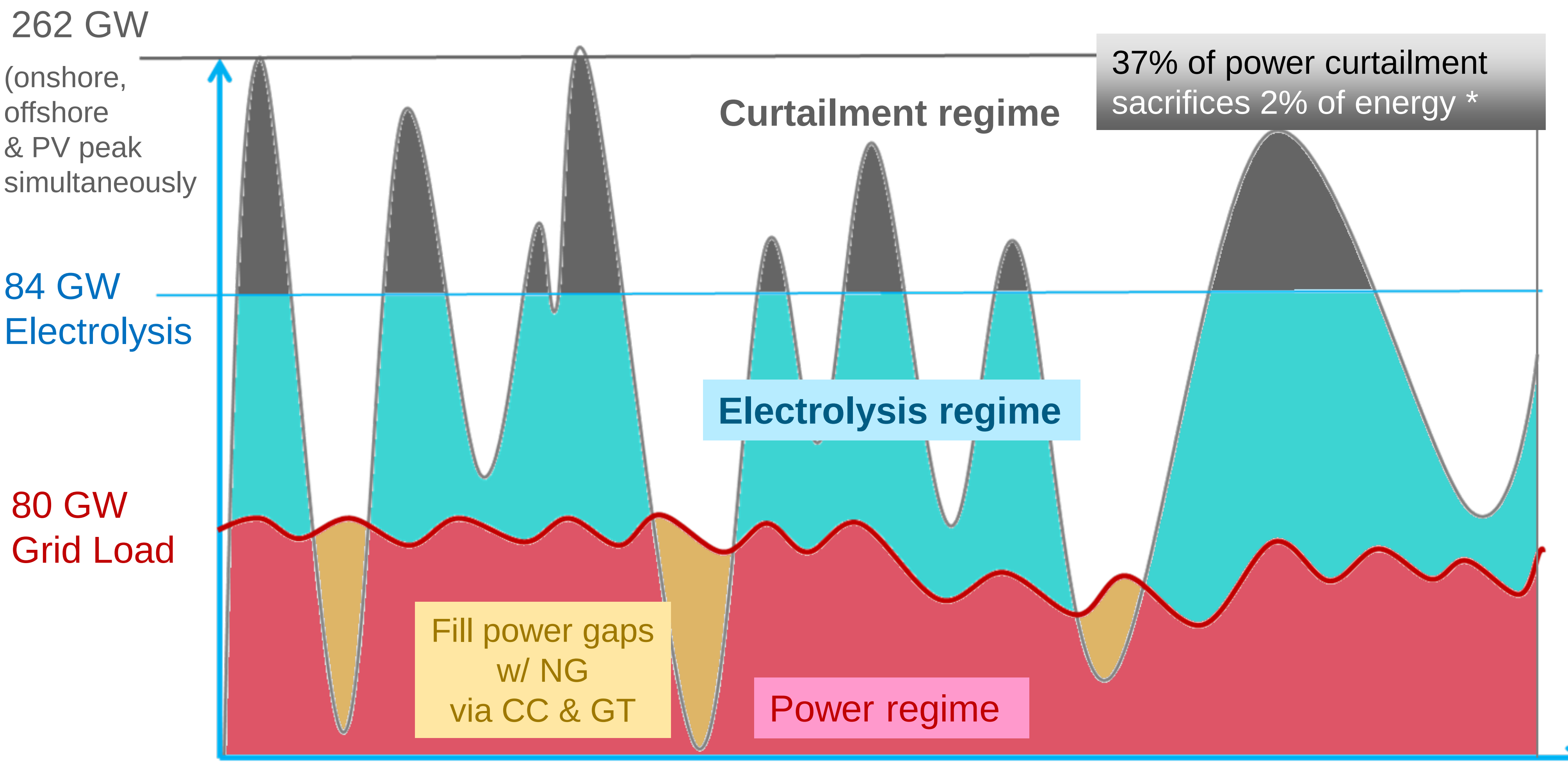
Picture of power poles from Hofman: Technologien zur Stromübertragung, IEH,
http://nvonb.bundesnetzagentur.de/netzausbau/Vortrag_Hofmann.pdf

Power Line and Gas Pipelines Compared

	380 kV overhead line	Natural gas pipeline §	Hydrogen gas pipeline
Type	4 x 564/72 double circuit	DN 1000 p_{in} = 90 bar	
Energy transport capacity	1.2 GW_{el}	16 GW_{th}	12 GW_{th}
Investment cost in M€/km	1 - 1.5	1 - 2	1.2 - 3

Principle of a Renewable Energy Scenario with Hydrogen

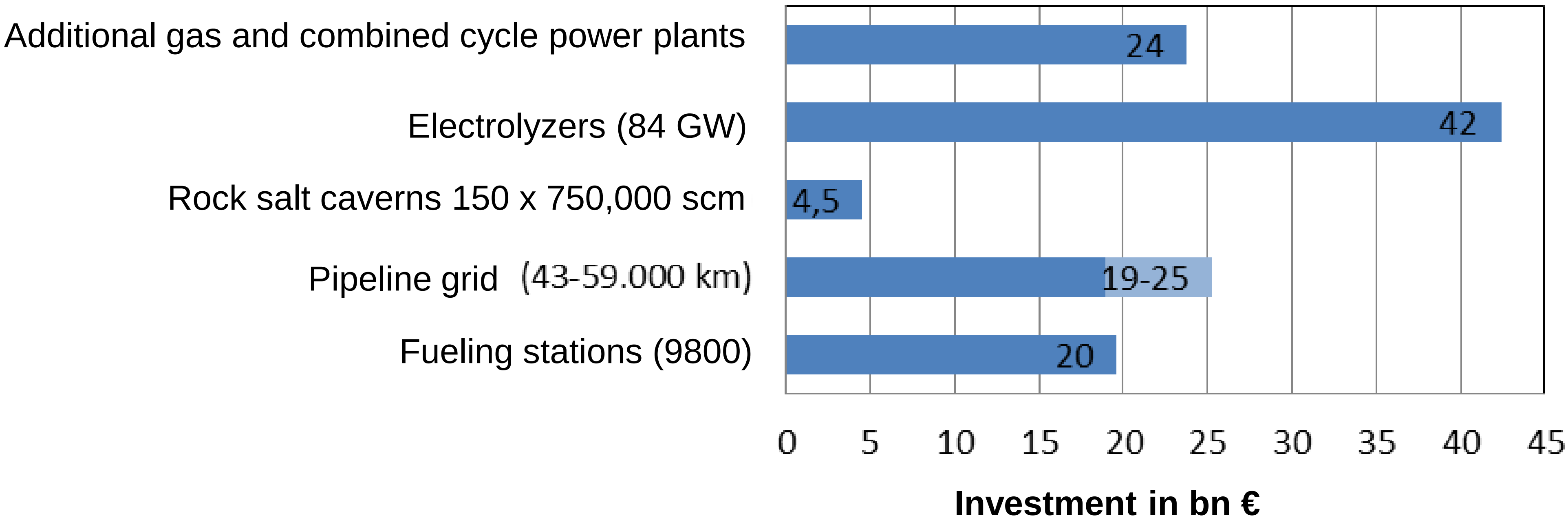
Hydrogen as an Enabler for Renewable Energy



* modeled for DE based on inflated input of renewables w/ weather data of 2010

Cost of Infrastructure

Overview on Cost for a Renewable Hydrogen Infrastructure for Transportation



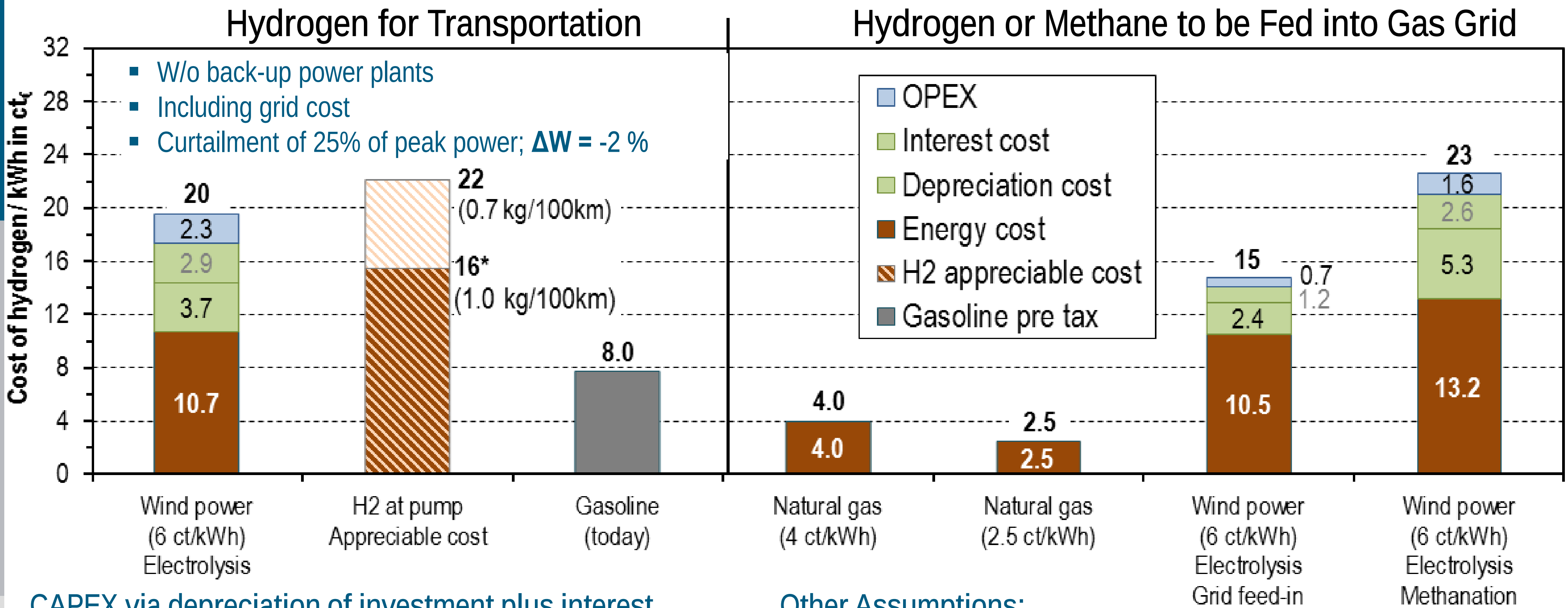
Cost Estimation of Battery Charging Infrastructure for Vehicles in DE

	1 Million BEV		30 Million BEV	
Percentage of private garages	100%		37% [1]	
Public charging stations per vehicle	0,25–0,5		0,7 -1,4 (McKinsey: 1,4)	
	Number Million units	Cost bn €	Number Million units	Cost bn €
Private charging (garage), 1,000 € each	1,0	1,0	11	11
Public charging stations, 6,500 €[2] each @ 40kW	0,25 - 0,50	1,6–3,3	21–42	136–273
Grid extension, 700 € each	negligible	-	32–53	22–37
Total in bn €		2,6–4,3		169-321

[1] Data from: BEHRENDS, S.; KOTT, K.: *Zuhause in Deutschland - Ausstattung und Wohnsituation privater Haushalte, Ausgabe 2009.* Statistisches Bundesamt, Wiesbaden, Wiesbaden, 2009.
Information used: 63% of households in DE (39,1 mn @ 2009) dispose of a garage / parking space; thereof 61% are used by the owner

[2] Data from: *Zweiter Bericht der Nationalen Plattform Elektromobilität.* Nationale Plattform Elektromobilität (NPE), Berlin, 2011;
Information used: cost for charging station, metering and automated settlement, installation of charging station, connection to electric distribution grid, designation of e-parking space, cost for right of dedicated use (average values, respectively)

Cost Comparison of Power to Gas Options – Pre-tax



CAPEX via depreciation of investment plus interest

- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid
- Interest rate 8 % p.a.

Other Assumptions:

- 5.4 million t_{H2}/a from renewable power via electrolysis
- **Electrolysis: η = 70 %$_{LHV}$**, 84 GW; investment cost 500 €/kW
- **Methanation: η = 80 %$_{LHV}$**
- Grid fee for power transmission: 1.4 ct/kWh$_e$ [1]

* Appreciable cost @ half the specific fuel consumption

[1] **EWI (2010)**: *Energiekosten in Deutschland - Entwicklungen, Ursachen und internationaler Vergleich (Projekt 43/09); Endbericht für das Bundesministerium für Wirtschaft und Technologie*. Frontier Economics/EWI, 2010.

Conclusions

- A fully renewable energy supply entails overcapacity in installed power and hence "excess power"
- 80% of CO_2 reduction requires interconnection of the energy sectors
    - Battery vehicles
    - Hydrogen vehicles
    - Hydrogenation steps in liquid fuel production from biomass and CO_2
- Conversion of excess power to hydrogen and storage thereof is feasible on the scale needed (TWh)
- Over long distances mass transportation of gas is more effective than that of electricity
- Battery vehicles are being introduced to the mass market
- cell vehicles are being introduced to the market by asian automakers
- Hydrogen as an automotive fuel is cost effective other than feed-in to the gas grid or reconversion to electricity

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